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At the crossroad between green and thirsty: Carbon emissions and water consumption of Spanish thermoelectricity generation, 1969–2019

Sara Cano-Rodríguez [a,*], Mar Rubio-Varas [a], Diego Sesma-Martín [a,b]

[a] *Institute for Advanced Research in Business and Economics (INARBE), Public University of Naverre (UPNA), Jerónimo de Ayanz Centre, Arrosadia Campus, 31006 Pamplona, Spain*

[b] *Department of Economics and Business, University of La Rioja, Quintiliano Building, 26004 Logroño, Spain*

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ABSTRACT

The energy sector is the main contributor to greenhouse gas emissions and one of the thirstiest sectors worldwide. Within the energy sector, thermoelectricity directly impacts on both emissions and water. This study assesses the evolution of the direct CO_2 emissions and operational water consumption of the Spanish thermoelectricity generation from 1969 to 2019. Both carbon emissions and water consumption correlate over time, led by the trends in total thermal generation, although over the past half century, water requirements swelled far more than carbon emissions. This results in a long-term trade-off between carbon emissions and consumptive water use in relative terms: while the CO_2 per thermal MWh generated halved since 1969 in Spain, the operational water consumption per MWh of thermoelectricity generated more than doubled due to switching from coal burning to nuclear and combined cycle technologies. We find no real trade-off in absolute levels. Although moving towards smaller environmental impacts since the mid-2000s, thermoelectricity remains one of the largest carbon emitters while becoming one of thirstiest energy technologies in Spain.

1. Introduction

The burning of coal, natural gas, and oil for electricity and heat is the largest single source of global greenhouse gas emissions (IPPC, 2014). Among those, thermoelectricity generation continues to be the single largest emitter (IEA, 2019). In parallel, the energy sector is the second thirstiest sector worldwide -after agriculture- with about 10% of the world's total withdrawals and 3% of total water consumption worldwide (Terrapon-Pfaff et al., 2020). Also 88% of global power generation is water intensive (OECD/IEA, 2016). Electricity is the fastest-growing source of final energy demand as it progressively replaces fossil primary energy supply. Over the next 25 years, electricity growth is set to outpace that of total energy consumption (IEA, 2020).

Remarkably, the electricity sector has managed to become the sector with the largest emission reductions from 1990 to 2019 in Europe, thanks to less carbon intensive fuels, the advancements of greener technologies and the improvements in efficiency (EEA, 2021). Disappointedly, the percentage of electricity that comes from low-carbon sources today (39%) has remained almost unchanged from the mid-1980s (Ritchie and Roser, 2020). Meanwhile, high-carbon sources (e.g., fossil-fuelled) depend directly on water availability (Van Vliet et al., 2012). In fact, water is a critical input for energy (Averyt et al., 2011). Consequently, electricity generation is especially water intensive and represents a major driver of water stress worldwide (Mielke et al., 2010; Chini et al., 2018).

In addition to hydropower plants, thermoelectric power plants (that is, fuelled by coal, fuel oil, natural gas, or uranium) use significant amounts of water. In 2010, thermal power generation accounted for roughly 80% of global electricity generation and was responsible for almost one half of all water withdrawals in the United States and in

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* Corresponding author.
E-mail address: sara.cano@unavarra.es (S. Cano-Rodríguez).

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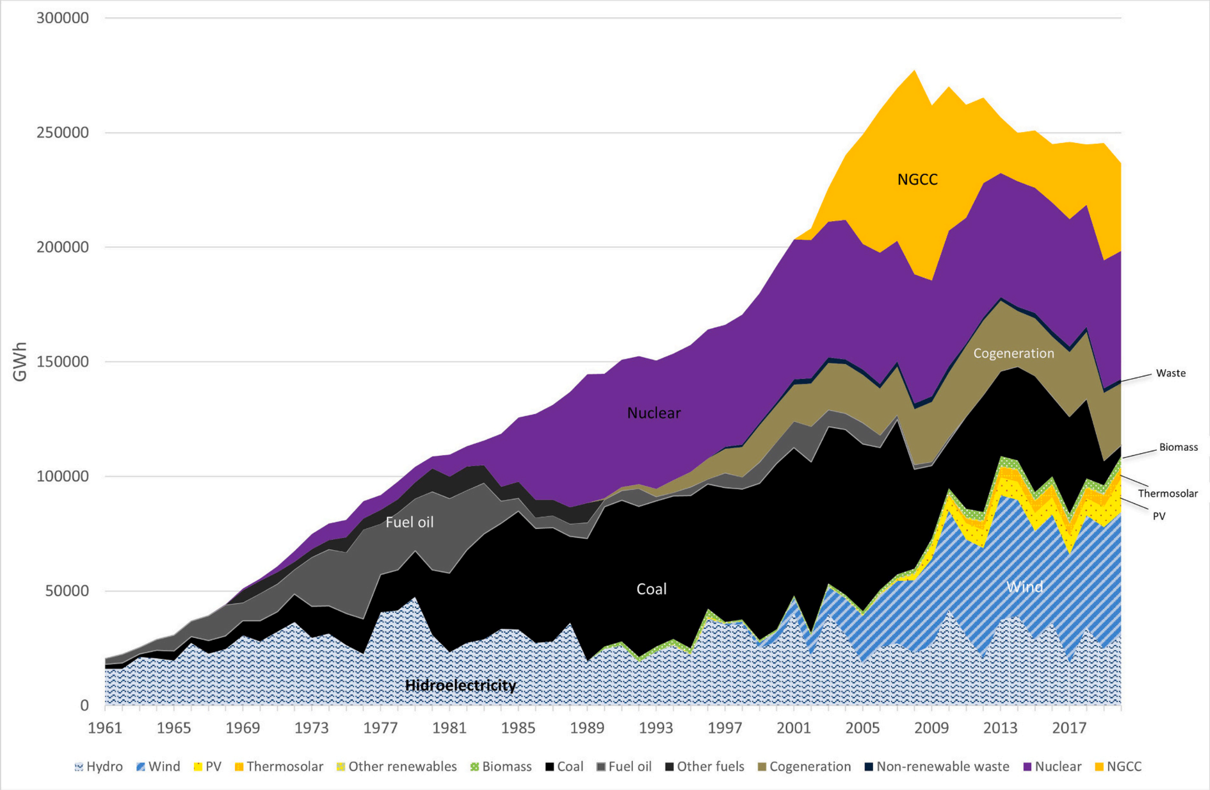

Fig. 1. Evolution of the Spanish electricity generation by technology (1961–2020).
Note: NGCC means natural gas combined cycle in the legend. Source: Own elaboration, data before 1969 from Estadística de la Industria Eléctrica del Ministerio de Industria, 1969 to 1990 Memorias anuales de UNESA. From 1990 Red Eléctrica de España. Peninsular system only (excludes Balearic and Canary Islands, and the autonomous cities of Ceuta and Melilla).

several European countries (IEA, 2012, 2013). Thermoelectric power facilities boil water to create steam. The steam is then used to spin the turbines which subsequently produce electricity through an alternator. Finally, the steam that has passed through the turbine is cooled to water before it can be reused to produce more electricity. Precisely, cooling is the process that involves the largest use of water in thermal power plants (Pan et al., 2018). The global thermoelectric water consumption increased by a factor of 18 between 1950 and 2010, driven by the expansion of the power sector and an increasing proportion of recirculating water-cooling systems[1] and it is expected to continue to grow as rising temperatures accompany climate change (Zhang et al., 2014).

For these reasons, it is worth analysing the CO_2 emissions of electricity generation as well as its use of water, which are both among the most important environmental impacts of energy besides waste and biodiversity impacts (IAEA, 2005). The possibility that decarbonization process might have spoiled the reduction of use of water should be discussed, since some alternative technologies, such as nuclear power, are zero-emitters but highly water-intensive. It is a key question to check whether electricity transition efforts can success in reducing carbon emissions and water consumption simultaneously. Currently, a growing number of authors are including the combined analysis of both impacts in their research because of the importance of understanding the different connections and interactions between them to support policymaking (Fang et al., 2014).

Measuring carbon emissions and water consumption has been originally carried out through the carbon and water footprint indicators, which belong to a broader footprint family of indicators for tracking human pressure on the environment (Ress and Wackernagel, 1996; Wackernagel and Rees, 1998; Galli et al., 2012). These footprints are characterised by including in their measurements both direct and indirect environmental impacts for a specified period over the life stages of an activity (Matthews et al., 2008; Wiedmann and Minx, 2008; Hoekstra et al., 2011). Nevertheless, in this paper we focus on direct carbon emissions and water consumption (i.e., the part of the freshwater withdrawn which is not returned to the original water body due to evaporation) in the operational phase of thermal power plants. Therefore, we leave aside other stages of the production process. Also, the potential indirect emissions are not considered here. The reason lies on the fact that direct emissions are the lion share of the electricity generation, unlike what happens in other sectors. Furthermore, the methodology would be so complicated that it would exceed the scope of the hole national sector. Finally, due to lack of actual data we also exclude from this study other water-related impacts such as water discharges, water returns to the environment with deteriorated quality, and water withdrawals, which provide an idea of the amount of water we initially need to run a thermoelectric power plant (Aldaya et al., 2021).

Spain was a pioneer country in the implementation of renewable generation technologies and has evolved towards a widely diversified electricity mix, reducing its CO_2 emitting technologies share in overall

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[1] There are two types of wet cooling systems: once-through cooling (open-loop) and evaporative cooling towers (recirculating cooling). Once- through cooling systems remove water from a body of water, pass it through a steam condenser, and subsequently discharge it into the same body of water at a higher temperature (usually limited by environmental law). Evaporative cooling towers expel the waste heat from the cooling water into the atmosphere. This cooling design reuses the cooling water in a second cycle instead of immediately returning it back to the original water source. Thus, cooling towers only withdraw water to replace the water lost to evaporation in the cooling tower. As a result, evaporative cooling towers entail less water withdrawal than once-through cooling but tend to involve significantly higher water consumption.

electricity generation over the last 40 years from 70% in 1981 to 20% in 2020 (see Fig. 1). In addition, Spain is one of the 33 countries in the world making use of nuclear energy. Even so, it is still among the seven largest CO_2 emitters within the European Union (EU). Regarding water use, Spain is the most arid country in Europe, and the percentage of electricity generation that relies on water has declined over the last two decades due to the shift towards renewable energy sources. However, more than 60% of the Spanish electricity generation still depends on the availability of fresh water in 2020 (that is all the thermoelectricity and the hydropower in Fig. 1).

In this paper we focus on the evolution of the direct CO_2 emissions and the consumptive water use of the Spanish thermoelectricity generation alone (coal, fuel oil, natural gas, and uranium). Although the thermoelectric sector has been the most important contributor to the Spanish electricity generation over the second half of the 20th century in Spain, there is an absence of studies analysing its dual environmental dimensions. By focusing on the most impactful electricity generating technologies, both in terms of emissions and water consumption, we aim at elucidating whether there has been any improvement in the environmental impacts within the thermal sector overtime, and whether there is any trade-off between carbon emissions and water consumption. We estimate the direct carbon emissions and operational water consumption of thermoelectricity generation in Spain for the period 1969–2019. For both, our estimation is primarily based on the aggregation of data published for individual power plants. Therefore, we focus on analysing the carbon emissions and water consumption in the operational stage of the thermoelectric power plants which allows us to show in more depth the driving forces.

The rest of the paper is organised as follows. In Section 2, we review those studies that separately assess the carbon emissions and water consumption of the electricity sector in Spain. Subsequently, we refer to the literature that jointly analyses both impacts for other sectors and different parts of the world. In Section 3, we describe the methodological approach and the data used to conduct the analysis. In Section 4, we present the results of our analysis. Finally, in Sections 5, we present the discussion and conclusions.

2. Literature review

2.1. Studies on carbon emissions in the Spanish energy sector

The first carbon emissions studies in Spain analysed the whole energy sector (Alcántara and Roca, 1995; Labandeira and Labeaga, 2002; Tarancon and Del Rio, 2007; Alcántara and Padilla, 2003) as the earliest authors did in other countries (Proops, 1988; Lenzen, 1998; Munksgaard and Pedersen, 2001; Machado et al., 2001; Ferng, 2003). These analyses based on *input-output* methodology ranked electricity amid the head emitters of CO_2 around 30%, only behind transport and followed by industry.

Further studies, at the end of the mid-2000, began to focus on the electricity sector alone and their direct emissions associated, by focusing on the generation mix. Within these specific analysis on electricity sector, Tarancón Morán et al. (2007) proved that the carbon emission factor by fuel type improved in a negligible way in Spain during 2000's, being almost fix, so according to this, it is necessary to inquire into the type of technology used. Other calculations including direct and indirect emissions were conducted (Sánchez et al., 2011; Aldao et al., 2019; López-Peña et al., 2011) by identifying coal, fuel oil, and natural gas combined cycle (NGCC, hereafter) power plants -from higher to lower impact- as the main responsible for electricity emissions in Spain. Likewise, almost all remarked the potential of renewables to cut the emissions, whereas other cost analysis considered combined cycle (Santamaría and Linares, 2011) and nuclear power (Delgado et al., 2011) too as alternative low-carbon sources due to their competitive prices. Nevertheless, there are no clear conclusions about the most suitable technological trends in long-term to achieve full decarbonization.

More recently, Piłatowska et al. (2020) presented a long-term analysis based on Threshold Vector Autoregression (TVAR) model to analyze the emissions of electricity consumption in Spain. It reveals a persistent positive relation between CO_2 and economic growth throughout 1971–2018 period, even during the development of nuclear power in the 1980s, the gas *boom* and the irruption of renewables from the 2000s. The authors noticed that the advance of less emitting technologies (nuclear and renewable sources) seems insufficient by themselves to reduce the total emissions as electricity generation growth offsets the gains of technological change. According to this study, the rising trend of CO_2 emissions only bent as a result of the closure of coal power plants in 2018. Other authors point out the same effect of economic growth for Europe and the USA, blaming it for the upcoming non-compliance with the Paris agreement (Nieto et al., 2018; Liu and Raftery, 2021).

2.2. Studies on water uses in the Spanish energy sector

Water and energy are the most critical assets globally and both resources are intrinsically related (Webber, 2016). Since lack of water and energy are undoubtedly limiting factors for the development of economies, the international literature on the water-energy nexus has increased exponentially in recent years (Stillwell et al., 2011; Hussey and Pittock, 2012; Hamiche et al., 2016; Dai et al., 2018; Ding et al., 2020; Chini et al., 2020). Electricity generation is one of the main drivers of water stress worldwide (Chini et al., 2018). The type of generation technology and cooling system being key components in determining the quantities of water used in such processes (Spang et al., 2014). Additionally, future energy supply structure - and thus future water demand for power generation - is subject to high levels of uncertainty due to the ongoing global energy transition (Terrapon-Pfaff et al., 2020). For these reasons, previous studies have focused on estimating the quantities of water used by a wide range of generation technologies (Sovacool and Sovacool, 2009; Sanders, 2015; Peer and Sanders, 2016; Larsen and Drews, 2019; Vaca-Jiménez et al., 2019a; Jin et al., 2019). Among these studies, research focused on the thermoelectricity sector stands out (Byers et al., 2014; Liao et al., 2016) with the water footprint indicator as the most widely used tool (Mekonnen and Hoekstra, 2012; Mekonnen et al., 2015; Vaca-Jiménez et al., 2019b).

This kind of research has been overlooked for the Spanish case until very recently. Some early works made calculations of both the energy used in the water sector and the water used for energy production. These works also included prospective analyses based on policy objectives and energy projections (Carrillo and Frei, 2009; Hardy et al., 2010; Hardy et al., 2012). More recently, Sesma-Martín and Rubio-Varas published historical series on water uses resulting from electricity generation in conventional thermal and nuclear power plants in Spain, using real data from the electricity companies. First, Sesma-Martín and del Mar Rubio-Varas (2017) provided a long-term estimate of the water withdrawal and consumption during the operational stage of nuclear power plants in Spain. Later, Sesma-Martín (2019) extended the analysis to the rest of the thermal power plants located in the Ebro basin, the largest contributor to the Spanish electricity grid since the 1950s.

2.3. Joint studies on carbon emissions and water use

Sections 2.1 and 2.2. demonstrate that separate analyses of carbon emissions and water uses exist for the Spanish energy sector, but none, to our knowledge, studies them jointly. However, examples of such work exist for other countries and sectors. Most of the existing research that jointly analyses impacts in terms of both carbon emissions and water focuses on food production (Page et al., 2012; Bonamente et al., 2016; Rinaldi et al., 2016; Vasilaki et al., 2016; Carneiro et al., 2019; Sampaio et al., 2021), industrial processes (Francke and Castro, 2013; Mantoam et al., 2020; Pomponi and Stephan, 2021; Brizga et al., 2020; Berger

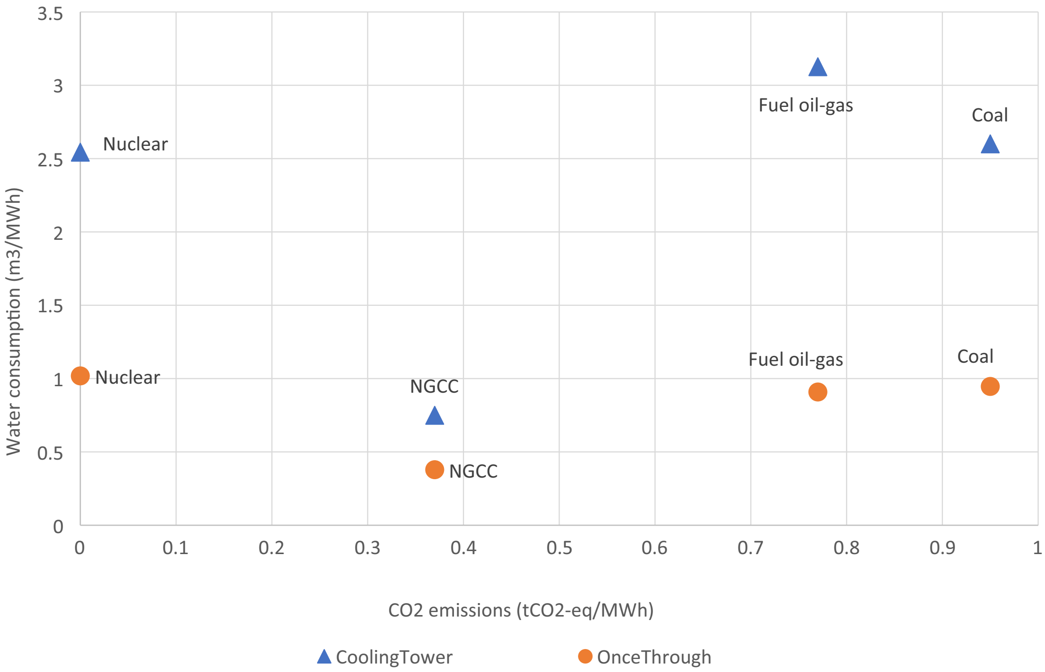

Fig. 2. Direct CO_2 emission and operational water consumption factors by type of thermoelectric generation technology.
Source: Direct CO_2 emissions and operational water consumption data come from Red Eléctrica de España (REE, 2021), and Macknick et al. (2012) and Spang et al. (2014), respectively.

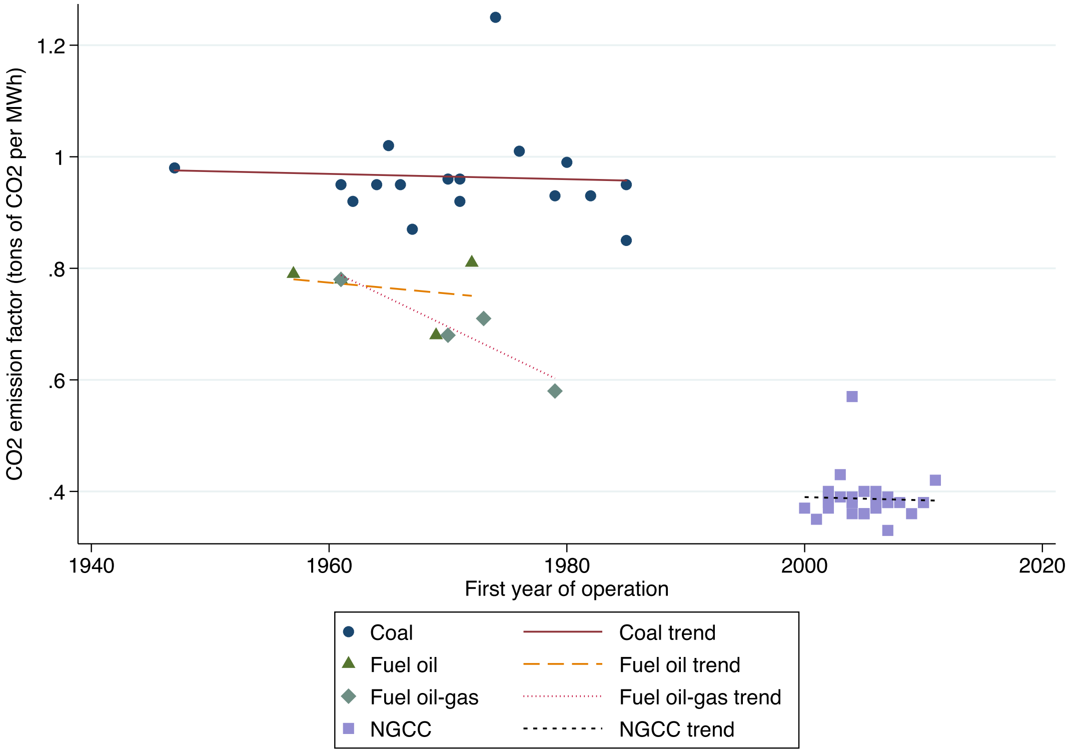

Fig. 3. Do newer plants pollute less? Average carbon emission factors of Spanish thermoelectric plants by year of initial operation.
Notes and sources: average CEF for each plant from State Registry of Pollutant Emissions, (MITERD, various years). First year of operation compiled from the Electrical Statistics of the Ministry of Industry. Trends are time linear trends.

et al., 2015; Ma et al., 2018; Qian et al., 2021), and service sector and residential activities (Kanakoudis et al., 2011; Gallion et al., 2014). All the above authors use the water footprint methodology in their estimates.

Research on impacts in terms of carbon emissions and water in the energy sector is still somewhat recent. Peer and Chini (2021) presented changes in carbon and water intensity for electricity from 1990 to 2018 for 145 countries. The authors showed increasing trends in the historical

Table 1
Summary of water (m3/MWh) and carbon (tonnes CO_2/MWh) factors by electricity generation technology in Spain.

Technology	Operational water consumption [Min-max range]	Direct Carbon emissions [Min-max range]
Coal	1.59–2.20	0.85–1.25
Fuel oil	3.13*	0.68–0.81
Fuel oil-gas	3.13*	0.58–0.78
NGCC	0.66–1.23	0.33–0.57
Nuclear	1.02–1.95	0

Notes: (*) No water consumption range is available for fuel oil power plants. A single technical factor is used throughout. Additionally, our database includes one power plant using Integrated Gasification Combined Cycle (IGCC) technologies with a factor in average of 0.76, which is not shown in the table. Sources: see text and supplementary materials. Supplementary Material contains detailed information on the sources of information used for CO_2 and water for each of the power plants considered.

evolution of both carbon footprint and operational water consumption of electricity technologies, with carbon estimates being higher. Mekonnen et al. (2016) forecasted the water footprint of electricity and heat in 2035 with reference to the four energy scenarios of the International Energy Agency (the Current Policies Scenario, the New Policies Scenario, the 450 Scenario and the Efficient World Scenario). Surprisingly, the IEA's "greenest" energy scenario, with the lowest carbon footprint, presented the largest water consumption because of the higher shares of hydropower and biomass, which both have relatively large water footprints per unit of energy output. Miller and Carriveau (2017) estimated the current balance between water and CO_2 emissions for Ontario's energy mix, by using footprints calculations. The results showed a ratio between water consumption and electricity generation of 8.7 m3/MWh in 2015 and a projected 13.0 m3/MWh by 2025. In terms of emissions, 0.075 t CO_2 eq./MWh were emitted in 2015 and the ratio was projected at 0.086 t CO_2 eq./MWh by 2025. Also, for the Canadian case, Gupta et al. (2021) developed an integrated model for understanding the water-GHG implications of decarbonizing the electricity generation sector for the horizon 2019–2050. The authors found that transitioning towards renewables can reduce GHG emissions and water consumption. Chen et al. (2020) compared the water and carbon footprints of shale gas with that of conventional natural gas and coal in China, by using a lifecycle analysis across power, residential and industry sectors. Their results revealed that the carbon footprint of shale gas is slightly higher than that of conventional natural gas, but still smaller than those of coal. Shaikh et al. (2017) found positive

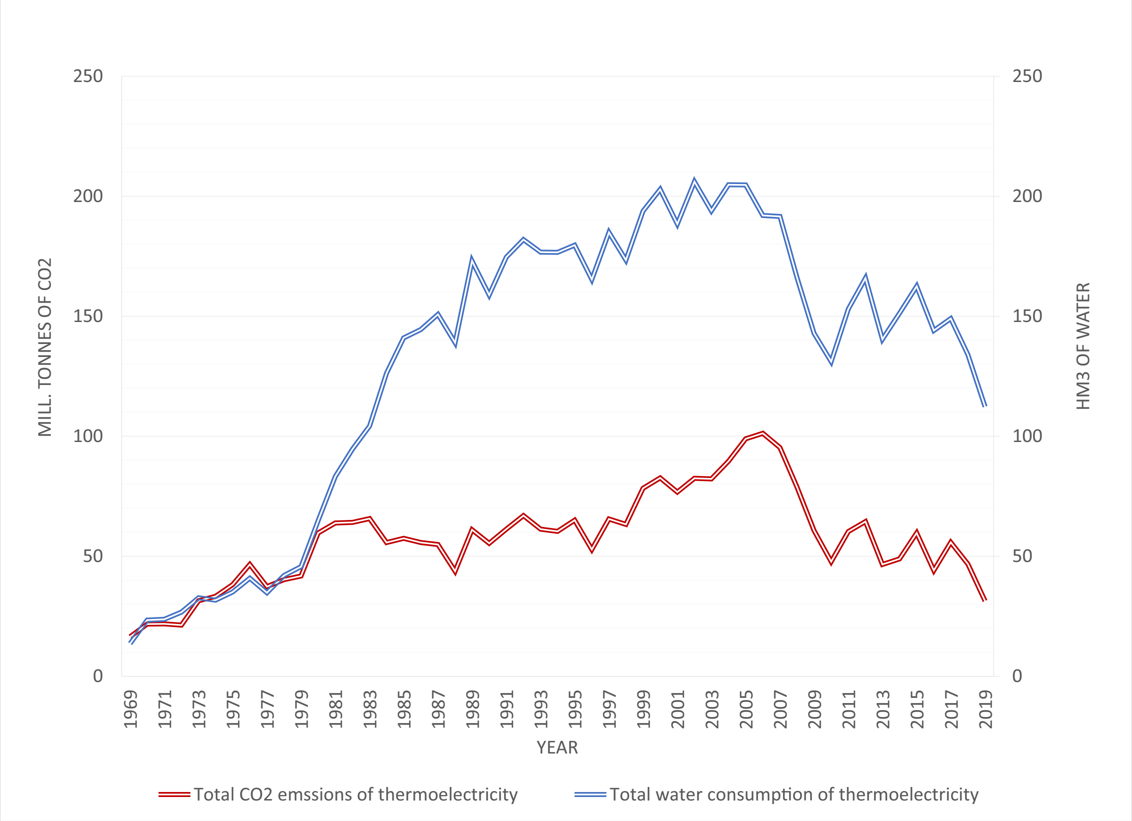

Fig. 4. Spanish carbon emissions (left-axis) and water consumption (right-axis) of thermoelectricity generation (1969–2019).
Note: The prefix 'hm3' refers to cubic hectometres. 1 cubic hectometre is equivalent to 100 cubic metres. Source: Own calculation from the environmental reports provided by electricity companies for water data and *Registro Estatal de Emisiones y Fuentes Contaminantes,* (MITERD, various years) for carbon dioxide.

Table 2
Growth and correlation of carbon emissions and water consumption (Absolute levels).

	1969–1979	1980–1989	1990–1999	2000–2009	2010–2019	1969–2019
CO_2 annual average compound growth rate	9.67%	3.90%	2.52%	−2.45%	−6.39%	1.30%
WC annual average growth rate	13.79%	14.24%	1.14%	−2.41%	−2.28%	4.63%
Correlation coefficient	0.94	0.09	0.92	0.78	0.91	0.82

Source: See Fig. 3.

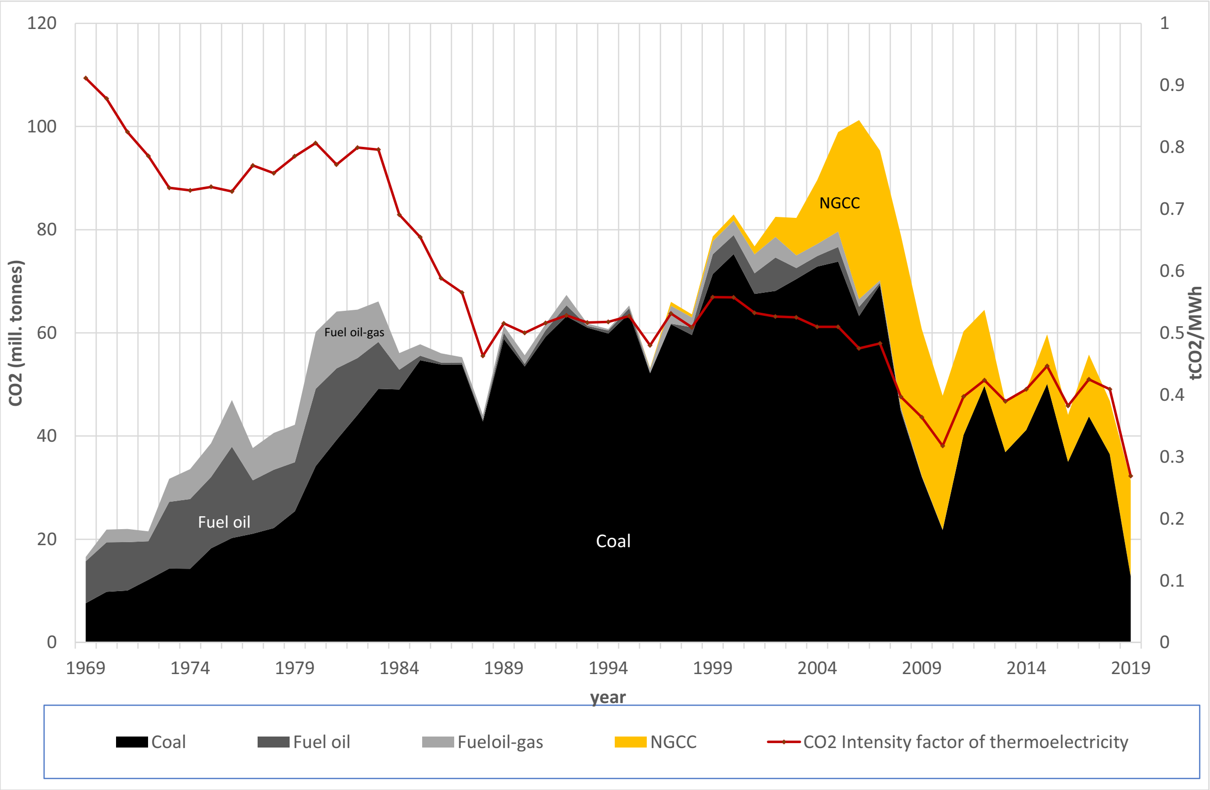

Fig. 5. Direct Carbon Emissions of thermoelectric power plants by type of generation technology (left axis, mill. tCO_2) and Carbon Intensity Index of thermoelectricity (right axis, tCO_2/MWh) in Spain, 1969–2019.
Source: Own calculation from *Registro Estatal de Emisiones y Fuentes Contaminantes,* (MITERD, various years).

correlations in carbon emissions and water use of possible energy mixes in Turkey under different scenarios: Business-As-Usual (BAU), Official Governmental Plan (OGP), and the Renewable Energy Development plan (REFDP). Results showed that REFDP scenario is preferable under the threats of increased water scarcity and the pressure to reduce carbon emissions. Coal and natural gas fired power plants ranked as the thirstiest and most polluting power plants in the country. Regarding methodological aspects, Siddik et al. (2020) compared seven common approaches for estimating the environmental footprint of electricity consumption to point out the importance of considering both the uncertainty of the underlying data used to calculate the environmental footprints, and the impact of the method selected to attribute the environmental footprints of electricity generation to the consumer. Other highlighted studies considering the interactions of both water consumption and CO_2 emissions within the electricity sector are Bello et al. (2018), Sharifzadeh et al. (2019) and Zhang et al. (2020).

All in all, the key question is whether there is a trade-off between emissions and water in electricity generation technologies. Fig. 2 offers a first glimpse of the issue for alternative thermoelectricity technologies showing that fuel oil and coal are worse in both fronts compared with nuclear power (or renewables, for what it matters that will be placed at the 0–0 corner of Fig. 2). Thus, in principle giving up coal power plants would have a double benefit both in terms of direct carbon dioxide emissions and operational water consumption.

3. Data and methodology

3.1. Data sources

To estimate carbon emissions and water consumption of the Spanish thermoelectricity sector we identified all thermoelectric power plants operating in Spain (peninsula only) between 1969 and 2019. Our focus is on the operational stage of the facilities, namely the electricity generation process. Our database included a total of 87 plants corresponding to all thermal power plants owned by the largest companies which were members of UNESA (Spanish Association of Electrical Industry) data base. UNESA's classification identifies the plants by type of generation technology and fuel used (coal, fuel oil, natural gas, and uranium) as well as the cooling system. These technical specifications affect the amount CO_2 emissions and water consumption. Thus, we gather a total of 24 coal plants, 16 fuel oil plants, 8 fuel oil-gas plants, 1 gasification combined cycle (IGCC), 31 NGCC plants and 10 nuclear power reactors (grouped in 7 plants). In the event of dual power plants (e.g., fuel oil- gas plants), we use the criteria based on the main fuel registered in the Spanish Official State Bulletin (BOE) (namely, BOE No. 102, 28 April 2007, pp. 4930–4930; BOE No. 29, 3 February 2017, pp. 8062–8070; BOE No. 61, 12 March 2003, pp. 9741–9753; BOE No. 113, 12 May 2017, pp. 39597–39,611). Only data for Peninsula are considered, excluding the Canary and Balearic Islands. Additionally, cogeneration technology is excluded from our calculations since none of the member of UNESA used this technology. Our final sample is representative since it covers a minimum of 70%to over 90% of total national thermal electricity generation throughout the period. Furthermore, a robustness and consistency analyses performed verifies a correlation coefficient of 0.96 between our sample collected and the total generation of the thermoelectric sector. Data on electricity generation in Spain from 1969 to 2019 comes from the annual reports of UNESA (UNESA, various years) and Red Eléctrica de España (REE, various years).

For these 87 plants over the period 1969 to 2019, the data readily available for CO_2 emissions and water consumption is the following. Studies discussing carbon direct emissions from electricity typically rely on an universal average factor emission per fuel obtained from the IAEA, the OECD or a similar body. That is the source used in the papers cited in the literature review above. Such studies are therefore assuming a fixed

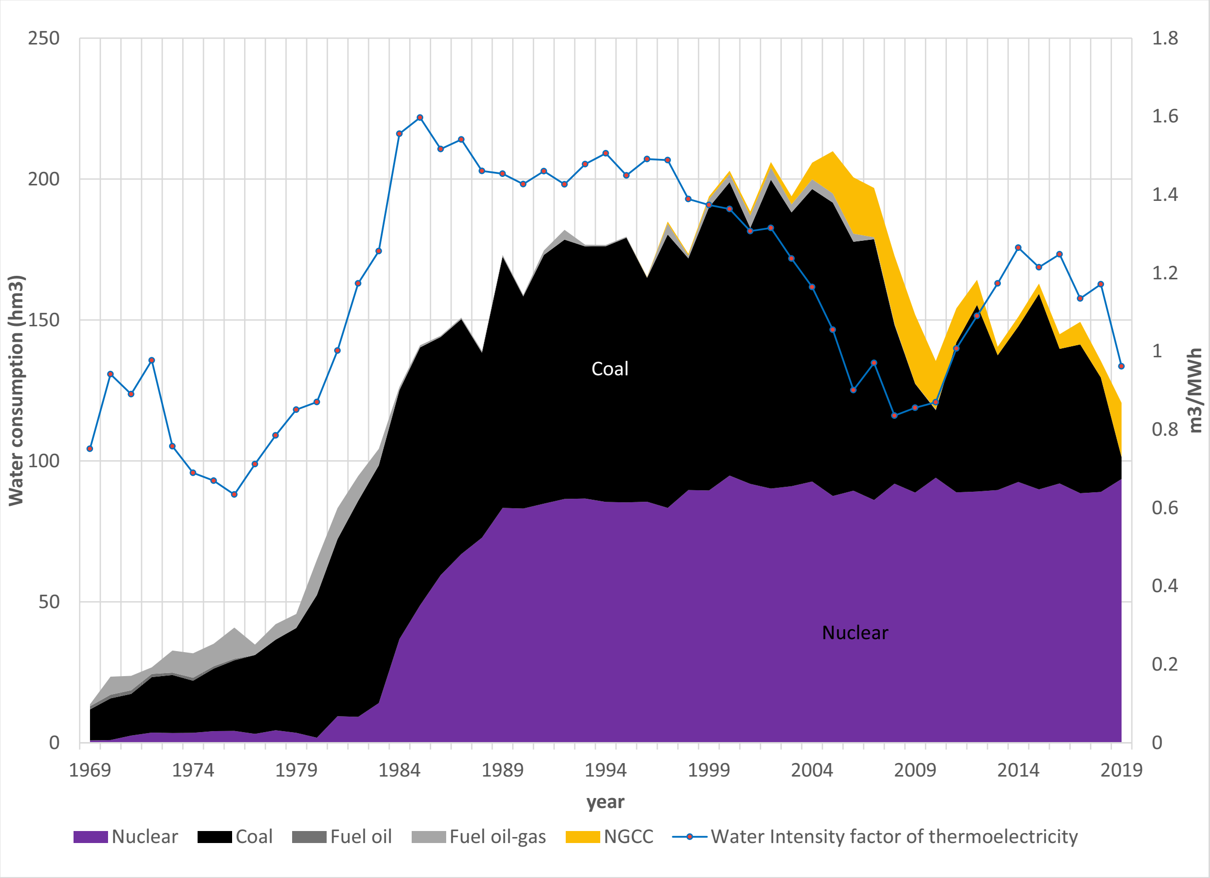

Fig. 6. Water Consumption from thermal power plants by type of generation technology (hm3) and Water Intensity Index of thermoelectricity (m3/MWh) in Spain. Source: Own calculation from the environmental reports provided by electricity companies for water data.

carbon emission factor over time but also an universal one: the same average for all plants burning the same fuel across the whole world. An average carbon emission factor by fuel type specific for Spain is available from REE (expressed in equivalent tonnes of CO_2 which contains not only CO_2 but also N_2O) (REE, 2021). However, this average from REE masks the variation across plants using the same fuel. Thus, we have collected emissions data by plant from State Registry of Pollutant Emissions, which is available from 2000 onwards (MITERD, various years). However, for twenty-five of the plants in our sample (seven coal, twelve fuel oil, two fuel-gas and four NGCC), we lacked specific plant data on emissions.

Public data on water uses per power plant were only available from mid-2000, when Spanish law made it compulsory for electricity utilities to publish environmental reports certified by the Eco-Management and Audit Scheme (EMAS). In other cases, we obtained non-public data from the power plants operators. Yet the data available is often inconsistent with the definitions and methodology used for water tracking (Sesma Martin and Rubio-Varas, 2019). In the water literature, the water consumption that is accounted for in the case of thermoelectric plants is that of fresh water for cooling, ignoring the plants that use sea water. In purity, operational water consumption data that is reliable, comparable, and methodologically consistent only exists 6 reactors (2 others are estimated, and 2 reactors non-using fresh water), for 8 of the 24 coal plants we have real data, (12 plants we estimated, 4 non-using fresh water) and for 3 of the 31 NGCC we have real data (for 6 we can estimate their water consumption, and 22 do not use fresh water). Finally for fuel oil and fuel oil-gas we have no real data of water consumption, but only two of those use fresh water (which we can estimate). The international literature comes to the rescue providing technical factors for different cooling systems and generating technologies (Macknick et al., 2012; Spang et al., 2014).

The next two subsections explain how we have built a robust CO_2 direct emissions estimate for Spanish thermoelectricity generation over the period 1969–2019, given the data just described, and the method used to estimate water consumption by thermal plants in Spain.

3.2. Estimation of CO_2 emissions

As explained above, from 2000 onwards annual direct emission data by plant belong State Registry of Pollutant Emissions, (MITERD, various years). For the 62 plants for which data is public for 20 years, the coefficient of variation of the individual carbon emission factor (CEF) is about 0. That is, plants did not pollute less over time from 2000 to 2019. Therefore, it is not heroic to assume that these thermoelectric plants pollute today as much as they did from their first day of operation. We use backwards the individual CEF for each of them with confidence. This is already an improvement over previous studies which apply the average CEF (available from the IAEA, the OECD or REE) to all plants utilizing the same fuel, since we know there exists variation across plants. Variation which has to do with a number of issues including the particular quality and mix of the fossil fuels employed in the different plants, the scale of production, but also the age of the plants: the plants operating in Spain belong to different technological eras. Do newer plants pollute less than older plants? Fig. 3 plots the average emission factor of every plant for which data is available against the year each plant became operational.

Fig. 3 makes evident several relevant issues. First, it shows the chronology of the technology choices for thermoelectricity in Spain: coal, fuel oil and fuel fuel-gas plants were all built before 1980s, none afterwards. The non-emitting nuclear plants (not plotted in Fig. 3) were

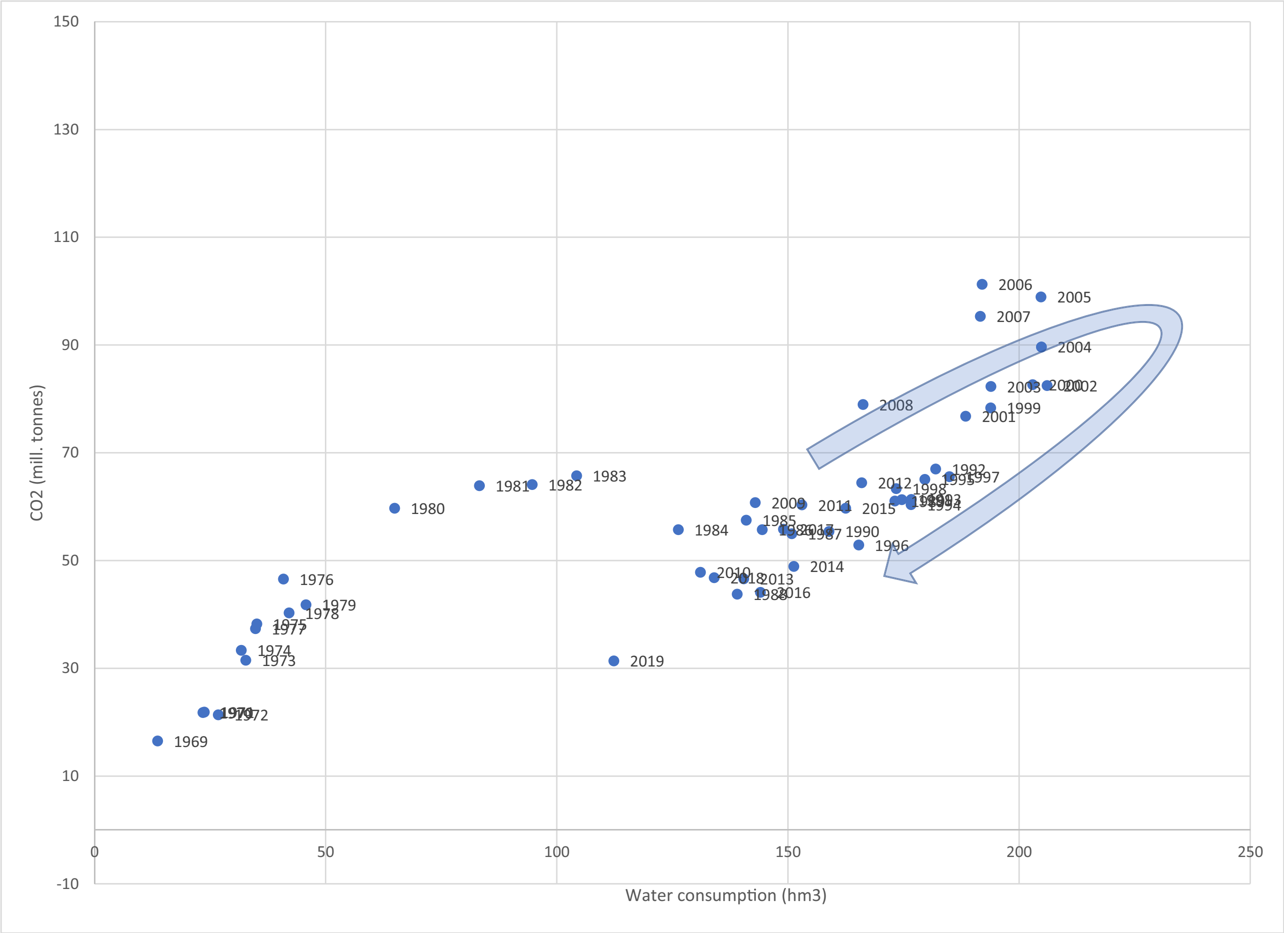

Fig. 7. Absolute trade-offs: Water Consumption from thermal power plants (hm3) vs Direct Carbon Emissions of thermoelectric power plants (mill. tCO_2) in Spain 1969–2019.
Source: Figs. 5 and 6.

all built from 1964 to 1988 within a period of large electricity demand growth. Per contrary, NGCC plants belong to the 21st century. Second, within each technology there are variations in CEF and different degrees of technological improvement over time. Coal burning plants and NGCC exhibit a small progress over time in terms of how much CO_2 they emit per MWh generated, as demonstrated by the trend lines. Observe that the trend we obtained for coal results in a CEF which is almost identical to the average CEF for coal plants provided by REE: 0,95 CO_2/MWh. However, fuel oil and, specially, fuel oil-gas exhibit more difference in their carbon factors between the older and the newer plants -from 0,78 to 0,58 tCO2/MWh, a 25% reduction for fuel-oil. Third, Fig. 3 hints that fuel switching is more effective in reducing emissions than any of the observed improvements in reducing emissions within the most polluting technologies generating thermoelectricity in Spain.

Our total emissions calculated by adding the CEF by plant is preferred as estimator rather than the one resulting from applying the average CEF offered by REE or the IEA per technology, since these slightly underestimate the emissions of the earlier period as they do not consider the variation across plants nor the technological improvement over time. Our consistency analysis indicates that our CEF proves to yield the least mean squared error. Even so, for the few plants for which there is no individual data available, we used the CEF of the closest plant within the same technology by opening date (by taking the average between the closest year of available data). In summary, when the CEF by power plant is available, carbon emissions (CE) for a single power plant *n* in year *t* are estimated as follows:

$$CE_t^n = CEF_t^n \times E_t^n$$

where CEF is the carbon emission factor (tonnes/MWh) of the plant and E is the electricity.

generated (MWh) by the plant considered. Thus, for a given year, total CO_2 emissions (tonnes) for the power plants considered are:

$$\text{Total } CE^n = \sum^{n} (CEF^n \times E^n)$$

3.3. Estimation of water requirements

Water used to generate electricity brings two concepts to the fore: water withdrawal and water consumption. The former refers to the total volume of water removed from the ground or diverted from a surface-water source for use. The latter represents the part of water withdrawn that evaporates and is therefore immediately removed from the aquatic environment (Kenny et al., 2009). Cooling is the process which involves the largest use of water. Cooling systems are classified into two categories: dry cooling and wet cooling. Each system entails different implications for water use due to their different functioning. In turn, wet cooling technologies are subdivided into two types: once-through and recirculating cooling. Open-loop systems remove water from a nearby source (i.e., river, lake, aquifer, or sea), circulate it through a steam condenser, and discharge the resulting warmer water into the original water body. By contrast, recirculating systems withdraw water and circulate it within the system, while air is forced through the circulating

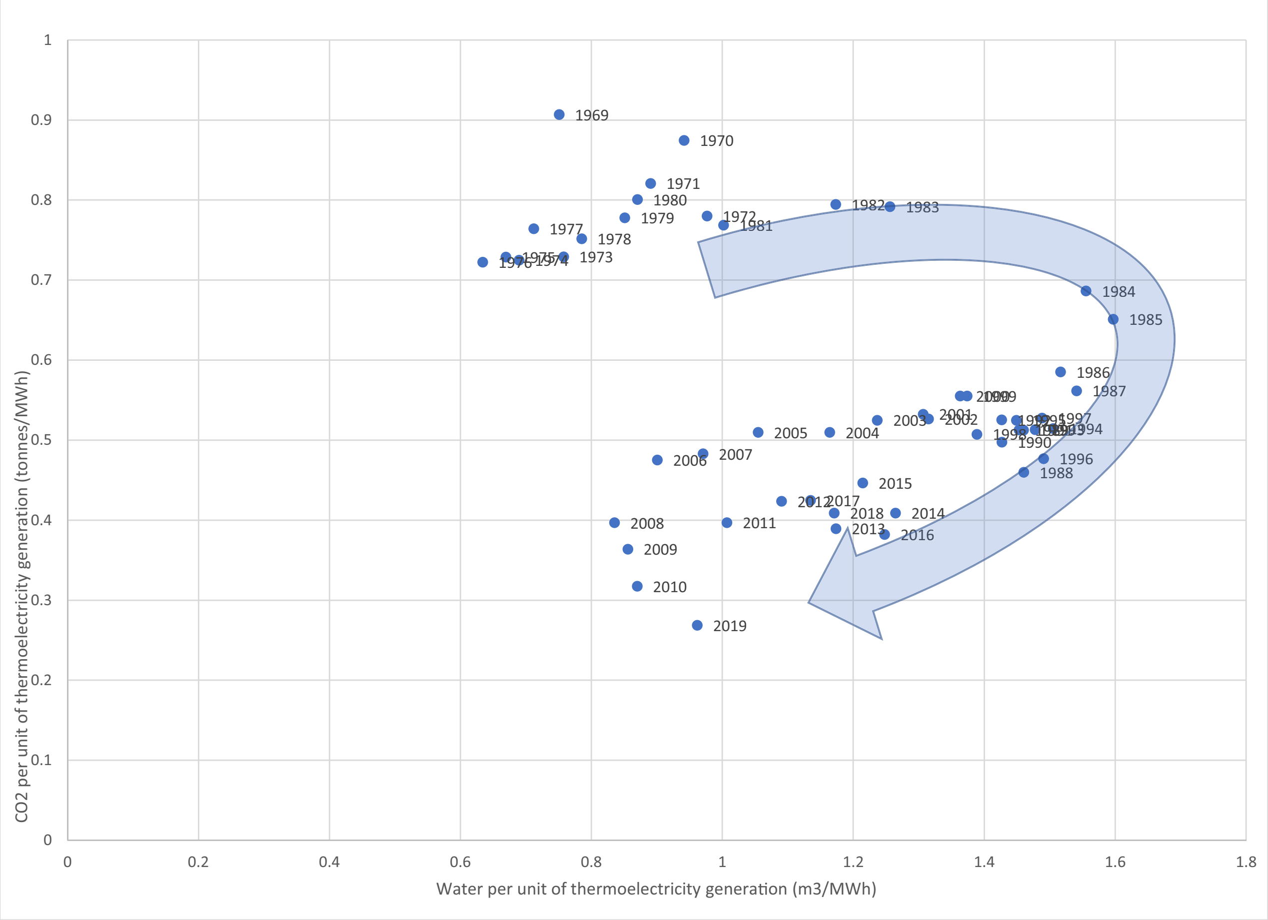

Fig. 8. Relative trade-offs: Water Consumption from thermal power (m3/MWh) vs Direct Carbon Emissions of thermoelectric power plants (tCO_2/MWh) in Spain 1969–2019.
Source: Figs. 5 and 6.

water flows. The waste heat from the cooling water is eventually expelled into the atmosphere through the tower. These systems have different quantitative impacts on water resources due to their different functioning. Once-through cooling systems have higher water withdrawals than cooling towers, while cooling towers involve higher water consumption (DeNooyer et al., 2016). Therefore, the type of fuel, power generation technology, and cooling system are the factors that determine the total water requirements of a thermal power station (Stillwell et al., 2011).

To estimate the operational water consumption of the Spanish thermoelectricity sector we follow the methodology used in Sesma-Martín and del Mar Rubio-Varas (2017). Operational water consumption refers to the part of the freshwater withdrawn which is not returned to the original water body due to evaporation during the cooling process in thermoelectric power plants.

For the years in which real data are available (from the mid-2000s onwards), we apply the corresponding water factor to the power plants. For earlier years, we calculate an average factor based on the available data per power plant and extrapolate the estimate backwards. In the remaining cases, the technical factors are borrowed from the literature. The operational water consumption of a single power plant *n* in year *t* is estimated by multiplying the corresponding intensity factor (WCF), measured in (m^3/MWh), and the electricity generated (E) in MWh. Formally:

$$\mathrm{WC}_t^n = \mathrm{WCF}_t^n \times \mathrm{E}_t^n$$

Thus, for a given year, the total water consumption (m^3/MWh) is:

$$\text{Total WC}^n = \sum^n \mathrm{WCF}^n \times \mathrm{E}^n$$

In summary, after making use of the data, methodologies and decisions just described the range of factors for emissions and water that we apply are shown in Table 1.

4. Results

Fig. 4 shows the evolution in absolute terms of the direct carbon emissions and operational water consumption series for thermoelectricity in Spain from 1969 to 2019. Both series run parallel between 1969 and 1980. Thereafter, the series diverge due to the commissioning of most of the Spanish nuclear power plants in the 1980s, which increase the water requirements of thermoelectricity while not increasing CO_2 emissions. Both series grew again from 1995 to the mid-2000s. From that date, carbon emissions and water consumption decline as a result of two forces: the overall reduction of thermal electricity output in Spain and the increasing role of less polluting and less water-consuming technologies such as NGCC -which, in addition, use seawater rather than freshwater. The reductions intensify when the coal plants closing process began from 2011 (see Fig. 1 above). As a result, CO_2 emissions over the 2010s return to levels equivalent to those of the late 1970s while water consumption come back to the levels of the late 1980s. In short, while thermoelectricity generation multiplied 12 times since 1969 in Spain, carbon emissions multiplied by 6 and water consumption by 16.

4.1. Trade-off between ccarbon emissions and water consumption results

As shown in Table 2, the correlation between direct CO_2 emissions and operational water consumption of thermoelectricity sector is close to 1 for most periods, that is, both impacts follow each other, and the same trend as thermoelectricity generation. This general finding requires some qualification within specific periods as well observing the evolution in relative terms (per MWh).

During the expansion period of classical thermal, from 1969 to 1979, both series worsened with a correlation of 0.94. Figs. 4 and 5 show that in that first period, coal and fuel oil power plants accounted for about half of carbon emissions each, but coal plants consumed 70% of the water, while fuel oil plants used 19%, with only 9% of water being attributed to nuclear. However, in 1980–1989, the introduction of nuclear power slowed down the accumulative average growth rate of emissions to 3.9% although boosting the rate of growth of water consumption to 14.2% (see Table 2). For that decade, the evolution of carbon emissions and water consumption almost disconnected from each other (their correlation falls to 0.09). Nonetheless, as nuclear power generation remained stable and coal power generation continued growing, the evolution of the carbon emissions and water consumption kept growing from 1990 to 1999. At the end of that decade, the impacts are yet more harmful in water terms. The CO_2 emissions had increased 1.7 times from 1980 to mid-2000s while water consumption had done it 3 times steeply from 65 hm3[2] in 1980 to more than 200 hm3, reaching nuclear power 40% on average of total water consumed by the thermoelectricity sector (coal power remains above 50%).

From 2005 until the present, the relation has turned into a "win-win" phase, by reducing both impacts (see Table 2). As thermal generation weaken and the classic thermal was replaced for combined cycle, the removal of both coal and fuel oil generated 70% fewer emissions -or 61 t avoided (90% belonging to coal plants and 8% fuel oil plants)- and a reduction of over 40% in water (some 50 hm3 less water most of which saved by closing coal plants) (see Figs. 5 and 6). Nuclear power plants maintain the water consumption at similar levels to the previous period, now becoming the largest water consumers of the thermoelectric power sector (more than 60% of the water), followed by coal (32%) and NGCC power stations (8%).

Over 2000–2010, combined cycle technology, which is a medium emitters and medium water consumer, cause the correlation carbon-water to remain positive but weaker. Finally, the last decade 2010–2020 it was that the first great simultaneous improvement took place in both emissions and water consumption because of the progressive closure of coal power plants and the overall reduction of thermal power generation.

In summary, as shown in Fig. 7, the thermal period shows no sign of trade-off since these are technologies intensive in both carbon emissions and water use; only the introduction of new technologies –first nuclear, then NGCC- changed the pattern towards more water required slowing the growth in CO_2 emissions. Finally, the combined effect of closing coal plus the overall reduction of thermal power brought about a reduction in both environmental impacts.

In relative terms, that is the carbon emissions and water consumption per MWh generated in thermal power plants (see Fig. 8), the story is a slightly different one. While the CO_2 per MWh generated shows a declining trend for the overall period with levels below half the ones it had in 1969 (see Fig. 5), the water consumption per MWh of thermoelectricity generated, after escalating to more than twice the levels of 1969, is today one and a half times larger than fifty years ago (Figs. 6 and 7). Therefore, in relative terms, our results in Fig. 7 indicate a trade-off between CO_2 and water consumption in the thermal electricity generation in Spain over the past fifty years.

5. Conclusions and discussion

We estimated carbon emissions and water consumption of the Spanish thermoelectric sector between 1969 and 2019. In relative terms, we found a trade-off between CO_2 emissions and water consumption over the period considered. However, in absolute terms, we only identified some trade-offs between 1980 and mid-2000s, when new generating technologies came into operation. This study showed the need to consider both carbon emissions and water consumption to better understand the impacts of the thermoelectricity sector and to improve policy decision-making in the ongoing energy transition process.

Our findings differed somewhat from previous research. Unlike what Piłatowska et al. (2020) affirmed, we find that CO_2 emissions of electricity generation did fall continuously during the last 15 years while total generation continued growing. This was possible because of a real technology substitution at a pace equal to or over the growth rates of electricity generation. While short-term studies for Spain attributed decarbonization solely to the introduction of renewable technologies (Tarancón Morán et al., 2007; Sánchez et al., 2011; Aldao et al., 2019; López-Peña et al., 2011), our results pointed at a decarbonization progress in relative terms over the long term within the thermoelectric sector mostly due to fuel switching, but a small part also played by technological improvements particularly in fuel-oil and fuel oil-gas. Yet as most of results in similar studies for electricity sector indicated, we confirm that carbon emissions and water consumption in absolute levels are positively correlated and improve with fossil-fuel plants retirements (Gupta et al., 2021; Miller and Carriveau, 2017; Chen et al., 2020; Shaikh et al., 2017; Miller and Carriveau, 2017). However, some of them pointed out the fact that water-intensive would get worse if coal were replaced by renewables such as hydropower. Finally, we can also confirm that the reduction of CO_2 has implied increasing water-intensity per MWh within the thermoelectric due to impact of nuclear power generation.

Some limitations and caveats must be introduced. In this study, we focussed on the operational impacts of thermoelectricity generation. Thus, we left out of the study the calculations of impacts of other production chain stages such as fuel supply and construction. Consideration of these indirect impacts as hole footprints will increase our carbon and water impacts calculations (Mekonnen et al., 2015). Likewise, our analysis left out the remaining of the electricity generation technologies. Renewable generation sources are zero-emitters and support the phase-out of polluting energy sources. However, some of them, such as hydroelectricity, have significant impacts on water consumption. A tentative application of the technical water consumption factors per country for Spanish hydropower of Mekonnen and Hoekstra (2012) would imply that our water calculations would rise to 95–247 cubic hectometres over the period analysed. In other words, our estimates of total CO_2 emissions will not increase much if we took the whole electricity mix rather than just thermoelectricity generation (since here we include the vast majority the emitting technologies), while our indicator on water consumption is the bare minimum since hydroelectricity is left out. We can be sure that in Spain the water consumption of electricity generation grew much more than the carbon emissions over the past half a century contrary to the results of Peer and Chini (2021) who asserted that the growth of the carbon footprint from 1990 to 2018 for 145 countries is higher than that of water. Finally, a decomposition analysis to determine the influences of intensity, structure, and scale factors on changes in CO_2 emissions and water consumption would shed additional light on the analysis. These issues represent avenues for future research.

Currently, the Spanish energy sector is immersed in a major energy transition process. According to the Spain's National Integrated Energy and Climate Plan (PNIEC), the last coal-fired power plants are expected to shut down by 2030. The report also foresees the end of Spanish nuclear generation by 2050. The closure of such facilities will have a positive impact in terms of water, as both are water-intensive technologies. The end of coal power generation will also result in a reduction in

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[2] The prefix 'hm3' refers to cubic hectometres. 1 cubic hectometre is equivalent to 100 cubic metres.

the level of CO_2 emissions into the atmosphere. For its part, nuclear power represents a zero-emitter technology and may contribute a continuous share of generation to the electric grid. In this context, the electricity no longer generated by thermoelectric generation technologies will have to be replaced by electricity from solar and wind technologies, which are dependent on climate and may not ensure sufficient generation at the times when it is needed. These are complex choices that still require research and deep reflection.

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Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Appendix A. Supplementary data

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